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# Beam-Beam'03 Summary*

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**Abstract.** This paper summarizes the presentations and discussions of the Beam-Beam'03 workshop, held in Montauk, Long Island, from May 19 to 23, 2003. Presentations and discussions focused on halo generation from beam-beam interactions; beam-beam limits, especially coherent limits and their effects on existing and future hadron colliders; beam-beam compensation techniques, particularly for long-range interactions; and beam-beam study tools in theory, simulation, and experiment.

## INTRODUCTION

The Beam-Beam'03 workshop was held in Montauk, Long Island, from May 19 to 23, 2003. It was attended by 15 participants from 9 institutions. Beam-Beam'03 was held in conjunction with with the 29th ICFA Advanced Beam Dynamics Workshop HALO'03. Part of the program, registration, abstract submission, and proceedings were shared with HALO'03. The workshop concentrated on beam-beam effects in circular colliders, with emphasis on hadron colliders, and followed earlier workshops on this subject [1, 2]. After a plenary talk on halo formation due to the beam-beam interaction, three main topics were discussed:

1. Beam-beam limits,
   especially coherent limits and their effects on existing and future hadron colliders
2. Beam-beam compensation techniques,
   particularly for long-range interactions
3. Beam-beam study tools
   in theory, simulation, and experiment

In the following we summarize the presentations and discussions for each of these topics.

## BEAM-BEAM HALO FORMATION

F. Zimmermann, CERN, summarized the measurements, simulations, and analytical models for the halo formation due to beam-beam interactions for both lepton and hadron colliders.

In lepton colliders, two beam-beam limits are observed: the first limit restricts the beam-beam parameter $\xi$, the second limit is due to the formation of transverse tails (Seeman, 1983). Tails in lepton colliders reach a 'steady state' due to radiation damping. They cause experimental background, reduce the beam lifetime, and often limit the luminosity. Dramatic increases of both core and tails were observed with increasing beam currents.

With no radiation damping in hadron colliders, the betatron amplitudes of particles in the tails are not reduced. Tails not only cause background, they can damage collimators and quench a superconducting machine.

A number of mechanisms for halo generation were considered in the past, among them beam-beam bremsstrahlung (Burkhardt et al., 1997), stochastic diffusion (Cornelis, 1993), Arnold diffusion (Chirikov, 1979), resonance trapping (Chao, Month, 1974), phase convection (Gerasimov, 1990), resonance streaming (Tennyson, 1980), and modulational diffusion (Chirikov, 1979). Transverse tails were most often measured with the help of collimators. In LEP, beam-beam bremsstrahlung was found to be the dominant tail generating process.

Halo generation in lepton colliders was studied with a number of computer codes. Self-generated boundary conditions were proposed by Irwin in 1989, and subsequently implemented in two codes. In addition, macro particle and PIC codes were developed. Typically $10^7$ to $10^9$ particle turns are tracked, and a good predictive power of these codes has been demonstrated.

Diffusive rates with beam-beam interactions in HERA and RHIC show similar values. However, the Tevatron in Run II and the LHC enter a new regime where long-range collisions dominate. These have caused fast beam losses in simulations and they may ensure that no tails develop.

Various tools are available to manipulate tails. Matched beam sizes, centered collisions, zero crossing angles and optimized tunes (with tolerances of approximately 0.001) were shown to be beneficial. Octupoles were used in VEPP-4, VEPP-2M, and DAΦNE.

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**TABLE 1.** Comparison of maximum beam-beam parameters in hadron colliders [4, 5, 6, 7]. Note that machine configurations change over time and that parameters in routine operation may be different.

| quantity | ISR | SPS | Tevatron Run II (design) | HERAp | RHIC p 2003 | LHC (design) |
|---|---|---|---|---|---|---|
| bunches per beam | coasting | 3 | 36 | 174 | 55 | 2808 |
| experiments (head-on interactions) | 6 | 2 | 2 | 2 | 4 | 4 |
| long-range interactions | ... | 4 | 70 | – | 2 | 120 |
| beam-beam parameter per IP $\xi$ | 0.001 | 0.009 | 0.01 | 0.0007 | 0.004 | 0.003 |
| total beam-beam tune spread $\Delta Q_{bb}$, max | 0.008 | 0.028 | 0.024 | 0.0014 | 0.015 | 0.010 |

## BEAM-BEAM LIMITS

In circular colliders the beam-beam interaction is one of the most limiting effects. The maximum beam-beam parameters achieved in hadron colliders are shown in Tab. 1. A table comparing lepton colliders can be found in Ref. [3].

Y. Alexahin, FNAL, reviewed the theory and observations of coherent beam-beam effects. The eigenmodes of coherent dipole oscillations can be found by solving the Vlasov equation in first order perturbation theory. At intensity ratios greater than 0.6, the discrete pi-mode lies outside the continuous spectrum and therefore may not be Landau damped. Multi-bunch modes with 36×36 bunches in the Tevatron were considered. The tune spread induced by the head-on and long-range interactions is large enough to damp the multibunch modes provided the tunes of both beams are the same. If the anti-proton tunes are lower than the proton tunes, the coherent modes shift by less than the incoherent tunes and may not be damped. A number of mechanisms were proposed to suppress the $\pi$-mode: a split of bare lattice tunes (A. Hoffman), redistribution of phase advances between interaction points (A. Temnykh, J. Welch), different integer parts of tunes in separate rings (W. Herr), and long bunches (due to the overlapping of synchrotron sidebands). During discussions, Alexahin suggested separating "collective" from "coherent", the former applying to purely intensity dependent phenomena, the latter applying to phenomena where particle phases are correlated.

L. Jin, University of Kansas, showed a case of collective instability in HERA. When the $e^+$-beam approached a fourth order resonance, a 30% emittance growth was observed in the proton beam. This observation could be well reproduced in a simulation. Later he discussed the importance of tune spread to the collective beam-beam instability.

W. Fischer, BNL, gave a presentation of strong-strong and other beam-beam observations in RHIC. With the current bunch spacing, bunches in RHIC experience only two long-range interactions. It is intended to accommodate a total tune spread as large as has been achieved in the past. Furthermore, RHIC is the first bunched beam hadron collider in which strong-strong effects are observed. Beam-beam generated $\sigma$- and $\pi$-modes were seen with a frequency difference that matches expectations from calculations [8]. The coherent modes observed could be suppressed by separating the tunes of the two rings. This may not be sufficient if the beam-beam parameter is doubled and the triplets are better corrected, leaving the beam-beam interaction as the dominant source of transverse nonlinearities.

In two talks the performance of the *B*-factories were reviewed. W. Kozanecki, CEA-Saclay/SLAC, showed the recent performance of the SLAC B-factory. A strong interplay between electron cloud and beam-beam effects is observed. With changing parameters along the bunch train, luminosity and background optimization relies on a delicate balance between currents, tunes, beam-beam and e-cloud parameters. Long-range interactions have an observable negative impact on the luminosity. As of May 2003, the tunes were moved closer to the half integer and were found to improve machine performance. Beam-beam simulations show encouraging agreement with experiments although not all relevant phenomena were included. The beam-beam parameters $(\xi_x, \xi_y)$ achieved in the LER and HER respectively are (0.065,0.048) and (0.075,0.060), the luminosity reached $6 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$.

K. Ohmi, KEK, reported on the experience with finite crossing angles at KEKB. With a crossing angle of 2x11 mrad a luminosity of $1 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ was achieved. No problems were encountered with the crossing angle up to a beam-beam parameter of $\xi \approx 0.05$. The beam-beam parameters $(\xi_x, \xi_y)$ achieved in the LER and HER respectively are (0.097,0.066) and (0.067,0.050). Electron cloud effects in the positron ring (LER) are mitigated (both in KEKB and PEP II) by wrapping solenoidal coils around most of the machine. As in PEP II, a day-by-day fine tuning of the machine parameters is required to maintain the highest luminosities. Simulations helped with the choice of the tuning parameters.

The use of crossing angles and long bunches is also under consideration for hadron colliders [9]. W. Fischer showed an example of a possible luminosity increase at the incoherent beam-beam limit with six superbunches in RHIC. Assuming that the incoherent tune shift is the limiting effect and neglecting a number of other effects, a luminosity increase of about two orders of magnitude was estimated.

T. Sen, FNAL, reviewed the theory and observations of beam-beam interactions in the Tevatron. One of the key observations is that a small tune footprint by itself does not guarantee good beam lifetime. At injection, the long-range beam-beam interactions (which create a small tune footprint) limit the anti-proton beam lifetime to 1-5 hours compared to 25 hours without the beam-beam interactions. No significant effect on the protons is seen. On the ramp, about 10% of the anti-protons are lost and the observed anti-proton emittance growth is suspected to be caused by beam-beam. During the beta-squeeze, anti-proton losses are low while proton losses are occasionally high enough to cause quenches. At collision, beam lifetimes are mainly determined by the $p-\bar{p}$ interactions at the detectors. Bunch dependent emittance growth of anti-protons due to beam-beam effects at collision is sometimes observed. This can usually be corrected by a change of tune. Changes to the helices, realignment of the Tevatron, cleaner IR optics, different bunch patterns and active beam-beam compensation are among the several methods under development to mitigate the effects of the beam-beam interactions.

B. Erdelyi, FNAL, compared simulations with experimental studies in the Tevatron. Until the recent commissioning of the vertical dampers, the vertical chromaticity was set to a high value to keep the protons stable at injection energy. This however lead to a low anti-proton lifetime and the emittance was found to decrease initially before reaching a constant value. From these observations, the dynamic aperture of anti-protons could be measured and was found to be in good agreement with the simulation results. At collision, lifetimes observed at different tunes were compared with dynamic aperture calculations at these tunes and found to be in qualitative agreement.

W. Fischer showed how the beam-beam interaction and unequal rf frequencies can generate tune modulation. This effect leads to a reduction of the beam lifetime in RHIC when the rf frequencies of the two rings are not locked, a situation typically encountered during the RHIC energy ramp.

# BEAM-BEAM COMPENSATION

Two approaches are currently pursued to compensate the long-range beam-beam interactions: electric wires and electron lenses. Attempts to compensate the direct space charge forces through four-beam schemes were not successful in the past, but are under investigation again. Also under investigation are the compensation of the beam-beam multipole effect with magnets. A short summary of earlier compensation schemes can be found in Ref. [10].

## Wire compensation at the SPS

The idea of compensating the long-range beam-beam interactions by the magnetic field of a current carrying wire was proposed for the LHC by Koutchouk. In the LHC the long-range interactions are clustered around each IP and occur at nearly the same betatron phase. Simulations showed that two wires placed around each IP reduced the tune footprints and increased the diffusive dynamic aperture by about (1-2)$\sigma$.

F. Zimmermann reported on recent experiments performed at the SPS to observe the effects of a single wire on a beam. A 1m long wire supported on a rigid structure and carrying 267 A of current was placed in the vacuum chamber. Water flow through the hollow wire was required for cooling. Orbit bumps were used to change the transverse separation of the beam and the wire. Beam lifetime dropped and background rates increased at separations smaller than 9$\sigma$ - close to the predictions from simulations. Orbit distortions and tune shifts due to the wire were also close to predictions. Diffusion rates could not however be measured.

These initial observations are indeed encouraging and suggest that the idea is worth pursuing. The next critical step is to demonstrate that the wire can compensate the effect of another field on the beam. The plan in the next stage of the experiment is to install two wires in the SPS. The second wire will be powered to cancel the effect of the first wire on the beam. If the experiment succeeds, the wire compensation idea will likely be pursued seriously not only for the LHC but also for the Tevatron and future hadron colliders.

## Multiple wires and modeling for the Tevatron

The wire compensation principle is also being tested at the Tevatron. The long-range interactions occur at different phases all around the ring and both beams traverse the same beam pipe. This necessarily makes the application of the wire compensation more complicated. One advantage is that the wire needs to operate only in a DC mode since the average effect on all bunches needs to be compensated.

B. Erdelyi discussed a fast and accurate model of the field of a finite length wire that allows misalignments and is now implemented in the codes COSY Infinity and SixTrack. First simulation results at injection energy with four wires placed in the Tevatron are encouraging. The maximum current required in each wire is estimated to be 232 Amps, a value close to the current used in the SPS measurements. At suitably chosen distances and angles of the wire relative to the anti-proton beam, the resonance structure excited by the wires resembles that generated by the long-range interactions. However the resonance structure depends sensitively on the placement of the wires suggesting a more robust compensation is necessary. One possibility is to place several wires in a cylindrical cage at each location. Initial investigations of the multiple-wire scenario show that the nonlinear components of the field created can be chosen with greater flexibility. Nevertheless, several issues with the wire compensation principle in the Tevatron need to be resolved before it can proceed to an experimental test.

## TEL results

V. Shiltsev (FNAL) reported on the status of the beam-beam compensation at the Tevatron with an electron lens. The Tevatron electron lens (TEL) was designed to counteract mainly the effects of the tune spreads between anti-proton bunches and the large tune footprint due to the beam-beam interactions at top energy. Initial observations showed that the tune shift due to the electron beam was as expected but the action of the lens usually worsened the lifetime. Unexpectedly the TEL found use as a resonant kicker in clearing the DC beam that circulates in the machine.

Recently the situation improved when the electron gun that generated a uniform rectangular profile was replaced by a gun that generates a smooth Gaussian profile. At good working points the electron lens preserves the beam lifetime. During stores the TEL has occasionally been used in an attempt to reduce emittance growth of selected anti-proton bunches. A recent attempt was successful but two other attempts had no influence or slightly negative effects. Several upgrades are planned to improve the performance of the lens - perhaps the most important will be reducing the orbit jitter of the electron beam.

## Multipole compensation

J. Shi, University of Kansas, proposed a method for compensating the nonlinearities of the beam-beam interactions with multipoles. This is achieved by minimizing the coefficients in a Taylor map of the nonlinear fields order by order. It was applied to a model of the LHC using either correctors locally in the IR sections or distributed globally in the arcs. It was demonstrated that the tune footprint could be reduced and the dynamic aperture increased using only up to third and fourth order nonlinearities of the map. The sensitivity of this compensation to lattice and orbit errors was not addressed.

## Four beam compensation

K. Ohmi reported on a new simulation study of the four beam neutralization scheme as a possible luminosity upgrade for KEKB. This scheme where beam-beam forces are canceled by virtue of no net charge at the collision points was first tried at DCI (Orsay) in the 1980s but did not succeed because of coherent instabilities. The DCI performance was compared with simulations earlier [11]. Two schemes were investigated in the present study.One scheme uses the present KEKB rings for two beams and two external beams are provided by linacs. In the other scheme two additional rings are built to have four circulating beams. Active feedback systems to damp the coherent dipole motion were included. However both schemes are plagued by higher order coherent and incoherent motion and the available tune space is very limited.

# BEAM-BEAM STUDY TOOLS

J. Ellison, University of New Mexico, showed averaging techniques in the weak-strong case with only head-on interactions, pointing to areas of high and low stability of particle motion in the tune plane. Averaged Hamiltonians were derived to describe motion in the vicinity of two low order resonances: the 4th order resonance $2\nu_x + 2\nu_y = p$ and the linear coupling resonance $\nu_x - \nu_y = 0$. The conjecture is that motion is generically chaotic in this neighborhood. He also presented a new model for the two degrees of freedom collective beam-beam interaction.

J. Rogers, Cornell University, reviewed beam-beam simulation methods for lepton machines. A key motivation for the simulations is to understand whether coherent or incoherent motion or some combination of the two is responsible for the two beam-beam limits observed in $e^+ - e^-$ machines. Weak-strong simulation methods require tricks to follow particle distributions long enough to calculate lifetimes, typically of the order of an hour or $10^9$ turns. These include the leap frog method of Irwin (1989) and inclusion of scattering processes by Kim and Hirata (1998). Weak-strong simulations have proven useful for accelerator design, the choice of operating parameters, and the investigation of beam halos (second beam-beam limit). Self-consistent strong-strong simulations are necessary to understand coherent effects but at present are able to follow particle distributions only for several damping times. Each $e^+ - e^-$ collider has developed its own PIC style code. These include CESR: Krishnagopal and Siemann (1996), Anderson (1999); PEPII: Cai et al. (2001); KEKB: Ohmi (2000). The luminosities calculated from these codes for their respective machines are found to be within 10% of observed luminosities when the machine is well tuned. A comparison of these codes is desirable.

J. Shi reviewed the simulations for hadron machines. Strong-strong methods currently employed include the soft Gaussian approximation, direct multi-particle tracking, Particles-In-Cell (PIC), Hybrid Fast Multipole Method (HFMM), and canonical perturbation theory for solving the Vlasov equation. It is important to check that convergence is achieved with respect to simulation parameters such as the number of macro-particles and the grid-size. Currently only fast processes (within $10^6$ turns) can be analyzed. Slow particle loss, emittance growth and the formation of tails cannot be predicted with confidence. Using a PIC style code, he reported chaotic motions of the centroid in a model of the LHC at ten times the design value of the beam-beam parameter. This is an interesting prediction but observation of this phenomena may be unlikely in the near future.

J. Qiang, LBNL, discussed the computational challenges in modeling beam-beam and space charge simulations. These include efficient Poisson solvers on parallel computers, large particle numbers, long tracking times, and stable direct solvers. He also discussed a parallel computational tool for strong-strong and weak-strong beam-beam modeling. The code is based on shifted Green functions and models efficiently the long-range parasitic collisions. The code was used to investigate the emittance growth caused by modulated transverse offsets in RHIC and the LHC. For the Tevatron, the antiproton lifetime at injection has been simulated. The calculated lifetime is of the order of a few hours (close to observations) when the physical aperture chosen is small enough.

A. Sobol, University of New Mexico, presented numerical calculations of the phase space density for the strong-strong beam-beam interaction that addressed the problem of storing a large amount of data into a computers cache.

Weak-strong simulation tools are useful standard tools for both lepton and hadron colliders. But while strong-strong simulations have gained predictive power for lepton colliders, their use for hadron colliders so far is limited. This should only encourage further development of codes and new methods such as the direct integration of the non-linear Vlasov equation.

In a discussion with the HALO diagnostics groups it was pointed out that for operational observations of the beam-beam effect, it would be desirable to have most beam quantities available on a bunch-by-bunch basis. Due to abort or other gaps in the bunch fill patterns, parameters such as closed orbit, tune, linear coupling, chromaticity and emittance vary from one bunch to another. Currently, bunch-by-bunch coupling, chromaticity and emittance measurements are not easily available.

## CONCLUSIONS

While there are a number of beam-beam phenomena, in both lepton and hadron colliders, that are not completely understood, the three major questions currently relevant to collider operation may be the following.

1. Are coherent modes dangerous in hadron colliders? They could be if the modes are outside the incoherent tune spread. However the spectrum of these modes and their relationship to the incoherent spectra depends on several factors including the intensity ratio of the beams, long-range interactions, synchrotron tune, chromaticity, tune splits etc. Until now the presence of these beam-beam driven modes has not limited the operation of any collider - either lepton or hadron. Damping mechanisms, e.g. changing the tune split or an increase in chromaticity, seem to be available to render these modes innocuous. That may change in the future so theoretical and experimental studies of these modes need to be vigorously pursued.
2. Can beam-beam compensations techniques be made to work? This is being actively studied experimentally and theoretically at the Tevatron, and at the SPS for application in the LHC. Both the electron lens and wires may be used in the Tevatron. The lens would be used to reduce the tune shifts between bunches and the wires to reduce the average effect of the long-range interactions on all bunches. The accelerator physics challenges are many: ensuring the proton beam is not affected, and coherent instabilities are not excited, to name a few.
3. What can analysis and simulations predict in hadron machines? Solutions of the linearized Vlasov equation with beam-beam interactions have been successfully used to predict the frequencies of pi-modes. Analytically it would be desirable to develop a weakly nonlinear theory that exhibits coupling of the modes and perhaps other features. Numerical tools to analyze the nonlinear Vlasov equation also need to be developed. Lifetime simulations for the Tevatron at injection energy are now yielding results, of the order of an hour, close to observations. Longer lifetimes are at present out of reach. Further improvements in the modeling and the use of the latest advances in computing technology are

greatly needed to run both weak-strong and strong-strong simulations for the time scales of interest.

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